The Interactive Ensemble Coupling Strategy for Quantifying ENSO Predictability

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Why Do We Use Ensembles?

- Quantify Uncertainty Due to Uncertainty in Initial Condition
  - Perturbed Initial States
- Quantify Uncertainty Due to Uncertainty in Model Formulation
  - Perturbed Model Formulation (Multi-Model)

- Understanding How Weather and Climate Interact
  - Why Climate Modelers Should Worry About the Weather
What if Your Coupled Model Has Incorrect Weather Statistics?

- ENSO Prediction Problem
- Western Pacific Problem

- Introduce the Interactive Ensemble Coupling Strategy
Weather - Climate Interactions

• One-way air-sea interactions (stochastic atmosphere, aka weather noise, forces ocean)
  – Ocean = thermodynamic “red filter”
    -- Hasselmann (1976)
  – Ocean-dynamics: preferred low frequency time scale(s)

• One-way air-sea interactions (stochastic ocean forces atmos.)
  – Tropical instability waves
  – Kuroshio current extension

• Two-way air-sea interactions
  – (Stable) coupled feedbacks + weather noise (MJO, WWB)
  – (Stable) coupled feedbacks + weather noise + dynamics
  – Unstable coupled feedbacks + weather noise + dynamics
Weather Noise as a Pacemaker for Climate: ENSO Example

1. Simplified “noiseless” coupled model (a la Z-C)
2. Random initial states
3. Identical prescribed idealized weather noise
How Should Weather Noise be Defined?

• **Use ensemble realizations**
  – Ensemble mean defines “climate signal”
  – Deviation about ensemble mean defines weather noise
  – Climate signal & weather noise are not necessarily independent

• **Examples:**
  • Atmospheric model simulations with prescribed SST
  • Climate change simulations
Different SST → Different tropical atmospheric mean response
Different characteristics of atmos. noise

SST Anomaly JFMA1998

SST Anomaly JFMA1989

Tropical Pacific Rainfall (in box)
Modeling Weather & Climate Interactions

- Previously, this required ad-hoc assumptions about the weather noise and simplified theoretically motivated models
- We adopt a coupled GCM approach
  - Weather is internally generated
    - Signal-noise dependence
  - State-of-the-art physical and dynamical processes

⇒ Interactive Ensemble
Interactive Ensemble Approach

Ensemble of $N$ AGCMs all receive same OGCM-output SST each day

AGCM_1
Sfc Fluxes_1

AGCM_2
Sfc Fluxes_2

\ldots

AGCM_N
Sfc Fluxes_N

average (1, \ldots, N)

Ensemble Mean Sfc Fluxes

OGCM receives ensemble average of AGCM output fluxes each day

SST

OGCM
Interactive Ensemble

- Ensemble realizations of atmospheric component to isolate “climate signal”
  - Ensemble mean = Signal + ε
- Ensemble mean surface fluxes coupled to ocean component
  - Ensemble average only applied at air-sea interface
  - Ocean “feels” an atmospheric state with reduced weather noise

850 mb Zonal Wind Standard Deviation

M = number of atmospheric ensemble members
Interactive Ensemble

Control SSTA
Unstable Coupled Feedbacks

Ocean noise?
Equatorial SSTA Variance

- One Atmos + One Ocean
- Six Atmos + One Ocean
- Six Atmos + Six Ocean
Understanding Forecast Skill

• What is the Overall Limit of Predictability?
• What Limits Predictability?
  – Uncertainty in Initial Conditions: Chaos within Non-Linear Dynamics of the Coupled System
  – Uncertainty as the System Evolves: External Stochastic Effects
• Model Dependence?
  – Model Error
CFSIE - Reduce Noise Version (interactive ensemble) of CFS
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RMS(Obs) * 1.4

CFSIE RMSE

CFS Spread

CFS RMSE

CFSIE Spread

CFSIE - Reduce Noise Version (interactive ensemble) of CFS
Worst Case: Initial Condition Error (A+O) + Model Error (WX)

Best Case: Initial Condition Error (A) + No Model Error (WX)

Better Case: Initial Condition Error (A) + Model Error (WX)
1. Eastern Pacific - Ocean Weather Noise - Tropical Instability Waves?
2. Enhanced Variance in Western Pacific - Not Enough Weather?
Western Pacific Problem

• **Hypothesis:** Atmospheric Internal Dynamics (Stochastic Forcing) is Occurring on Space and Time Scales that are Too Coherent
  ⇒ Too Coherent Oceanic Response
  ⇒ Excessive Ocean Forcing Atmosphere
  ⇒ **Test:** Random Interactive Ensemble
Ensemble of \( N \) AGCMs all receive same OGCM-output SST each day

\[ \text{AGCM}_1 \]
\[ \text{Sfc Fluxes}_1 \]

\[ \text{AGCM}_2 \]
\[ \text{Sfc Fluxes}_2 \]

\[ \ldots \]

\[ \text{AGCM}_N \]
\[ \text{Sfc Fluxes}_N \]

Average \( N \) members' surface fluxes each day

Average \( 1, \ldots, N \)

Ensemble Mean Sfc Fluxes

OGCM receives ensemble average of AGCM output fluxes each day

\[ \text{SST} \]

Interactive Ensemble Approach
Random Interactive Ensemble Approach

Ensemble of $N$ AGCMs all receive the same OGCM-output SST each day.

OGCM receives output of a single, randomly-selected AGCM each day.

Randomly select 1 member’s surface fluxes each day.

OGCM receives output of single, randomly-selected AGCM each day.
Nino3.4 Power Spectra

Increasing Stochastic Atmospheric Forcing Increase the ENSO Period
Nino34 Regression on Equatorial Pacific SSTA
Contemporaneous Latent Heat Flux - SST Correlation

Observational Estimates

Control Coupled Model

Increased "Randomness" Coupled Model

Random Interactive Ensemble: Increased the Whiteness of the Atmosphere forcing the Ocean
Random (Stochastic) Thoughts

• Interactive Ensemble Strategy for Quantifying Role of Stochastic Processes in Climate Variability

• Initial Condition Uncertainty is “Largest” Contributor to Loss of Predictability
  – Stochastic Processes also Important

• To Get the Climate Right Must Get the Weather (Statistics) Right
  – Seamless Prediction